412TW-PA-12673

FLIGHT TEST VALIDATION OF AN ANALYTICAL METHOD FOR PREDICTING TRAILING CONE SYSTEM DRAG FORCE AND DROOP ANGLE

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13 AUGUST 2012

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
13-08-2012

2. REPORT TYPE
Technical Paper

3. DATES COVERED *(From - To)*
August 2012-August 2012

4. TITLE AND SUBTITLE
Flight Test Validation of an Analytical Method for Predicting Trailing Cone System Drag Force and Droop Angle

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Reagan K. Woolf

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)
Air Force Flight Test Center
Edwards AFB, CA 93524-6843

8. PERFORMING ORGANIZATION REPORT NUMBER
412TW-PA-12673

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
N/A

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release A: distribution is unlimited.

13. SUPPLEMENTARY NOTES
CA: Air Force Test Center Edwards AFB CA   CC: 012100

14. ABSTRACT
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15. SUBJECT TERMS
F-16 Aircraft   static pressure   calibration   Reduced Vertical Separation Minimum   pacer   trailing cone

16. SECURITY CLASSIFICATION OF: Unclassified			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					412 TENG/EN (Tech Pubs)
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified	None	13	661-277-8615

Flight Test Validation of an Analytical Method for Predicting Trailing Cone System Drag Force and Droop Angle

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ABSTRACT

This paper presents flight test data that validate an analytical method for predicting trailing cone system drag force and droop angle. The method, presented in 2008 by Carlos Silveira, integrated a set of differential equations to solve for the pressure tube angle and aerodynamic drag force when given a tube length and cone drag coefficient. The length of tube and drag cone geometry may be chosen to place the static ports in the desired location behind the aircraft. This paper validates Mr. Silveira's method with tube angle and drag force data obtained from flight test on an F-16 aircraft equipped with a trailing cone system.

NOMENCLATURE

C_{D0}	Pressure tube drag coefficient [n/d]
ds	Incremental distance along the pressure tube [ft]
D_{tube}, D_{cone}	Drag force of tube and cone [lb]
g	Acceleration due to gravity [ft/sec^2]
K	Pressure tube drag roughness constant [n/d]
l	Length of pressure tube [ft]
L_{tube}	Lift force of pressure tube [lb]
r_{tube}	Radius of pressure tube [in]
T_0, T	Initial tension force and tension force, respectively [lb]
V_T	True airspeed [ft/sec]
W_{tube}, W_{cone}	Weight of tube and cone [lb]
x_0, y_0	Initial x and y coordinates (located at vertex of drag cone) [ft]
ρ	Ambient air density [slug/ft^3]
ρ_{tube}	Specific weight of pressure tube [lb/ft]
ϕ_0, ϕ	Initial droop angle and droop angle of pressure tube, respectively [deg]
ε	Drag cone half vertex angle [deg]

INTRODUCTION

Trailing cone systems are the preferred method for calibrating aircraft static air pressure measurement systems due to their ability to sense static pressure in the freestream air away from localized aircraft influences. Large transport aircraft typically use retractable trailing cone systems that can vary the length of tubing in flight. An optimum tube extension length may be determined in flight with relative ease.

However, for some types of aircraft wakes, there may not be an extension length that results in adequate trailing cone system performance. For example, if the drag cone

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and pressure tube “droops” into the engine exhaust plume or propeller wash, then the sensed pressure may not represent freestream ambient conditions. A potential solution in this example might be to use a larger drag cone that keeps the pressure tube above the jet wake.

Another example is an aircraft that uses a simple, fixed-length trailing cone system whose length cannot be varied in flight. In this case, various tube lengths must be evaluated by trial and error to determine an adequate length (reference 1). After testing the first tube length, the aircraft must land, have the tube length changed, and repeat the flight. This is an inefficient and costly way to determine the optimum tube length.

In both of these examples, a predictive method would be helpful for designing a trailing cone system that is compatible with the specific aircraft’s wake characteristics. In 2008, Carlos Silveira of Embraer presented an analytical method that predicted the droop angle and tension force of a trailing cone system given various design parameters such as tube length, diameter, specific weight, and cone drag coefficient (reference 2). His method, when combined with computational fluid dynamics simulations of the aircraft wake, could be used to design a trailing cone system that results in adequate sensing of freestream static pressure. The method integrated a set of differential equations to solve for the pressure tube angle and aerodynamic drag force given a tube length and cone drag coefficient. The length of tube and drag cone geometry may be chosen to place the static ports in the desired location behind the aircraft.

Mr. Silveira presented pressure data obtained from flight test that supported the method’s analytical predictions (reference 2). However, his paper did not include any tube angle or drag force data. This paper further validates his method with additional tube angle and drag force data obtained from flight test on an F-16 aircraft equipped with a trailing cone system.

OBJECTIVES

In 2007, 2009, and 2010, the U.S. Air Force Flight Test Center flight tested fixed-length trailing cone systems installed on an F-16 aircraft and determined the droop angles and in-flight loads exerted on the attachment point. The test data were used in a study to validate the analytical predictions using Mr. Silveira’s method. The objectives of this study were to:

1. Determine the aerodynamic drag forces on the trailing cone system and compare to analytical predictions.

2. Determine the droop angle of the pressure tube and compare to analytical predictions.

This paper presents the results of that study.

TEST ITEM DESCRIPTION

The test item was a fixed-length trailing cone system attached to the tip of the vertical stabilizer of an F-16 aircraft (Figure 1). The system consisted of a pressure tube, fire sleeve, static pressure sleeve, and drag cone. A diagram of the system is shown in Figure 2. Some of the flight tests used a static sleeve equipped with skids intended to protect the sleeve from damage while dragging on the runway during takeoff and landing (Figure 3).

Figure 1 F-16 Pacer with Trailing Cone in Formation with F-22

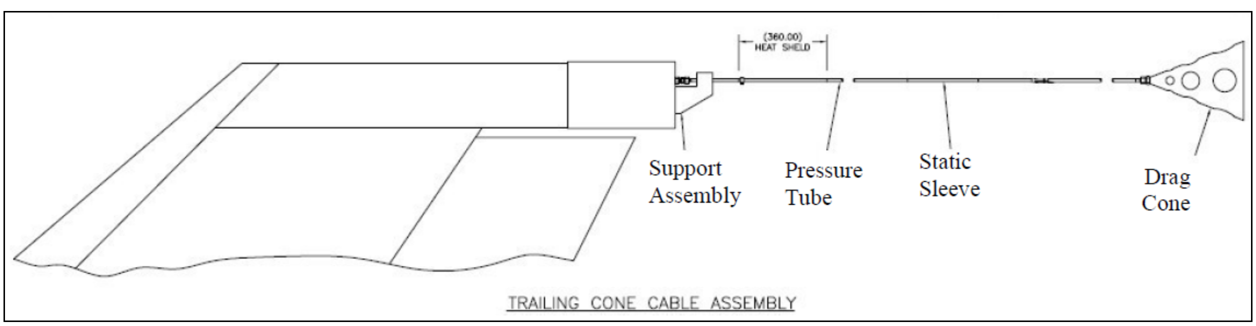

Figure 2 Trailing Cone System (without Skids) Attached to Tip of Vertical Stabilizer

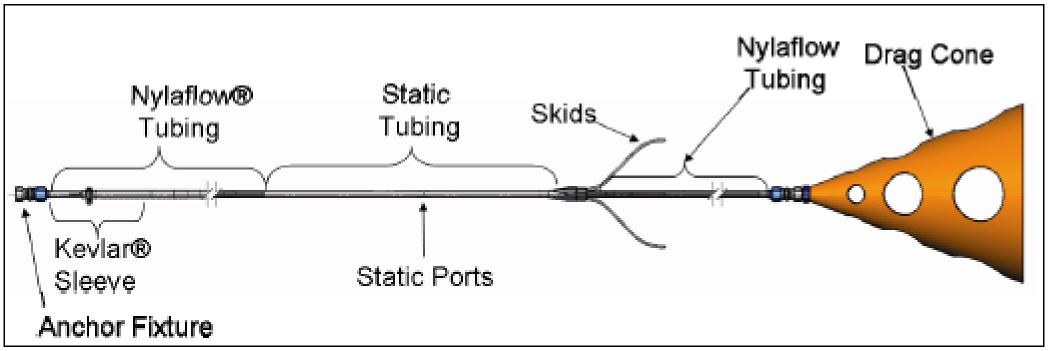

Figure 3 Trailing Cone System with Skids

The Nylaflow pressure tubing was approximately 65 feet in overall length between the attachment point and the drag cone. The static pressure sleeve was made of stainless steel and was located approximately 50 feet from the attachment point. The Kevlar fire sleeve covered the first 30 feet of tubing and was intended to guard against heat damage when the tube passed behind the engine exhaust. The pressure tubing was 3/8 (0.375) inches in diameter. The fire sleeve had a wall thickness of 1/8 (0.125) inches for an overall diameter of 5/8 (0.625) inches. A 0.094-inch stainless steel reinforcing cable passed through the inside of the pressure tubing. The pressure tube assembly had an average weight of 0.062 pounds per foot.

The composite fiberglass drag cone had a vertex angle of 42 degrees and a base diameter of 10 inches. The cone was connected to the pressure tubing using a swivel bearing assembly. The cone and swivel assembly weighed approximately 1.5 pounds.

Two types of load cells were used the measure the tension in the tube (Figure 4). The first type, flown in June 2009, was solid and prevented the pressure transducer from sensing static pressure. The second type, flown in August 2010, was hollow and allowed the static pressure to flow through the load cell to the pressure transducer. The load cells were installed between the attachment point and the pressure tube (Figure 5).

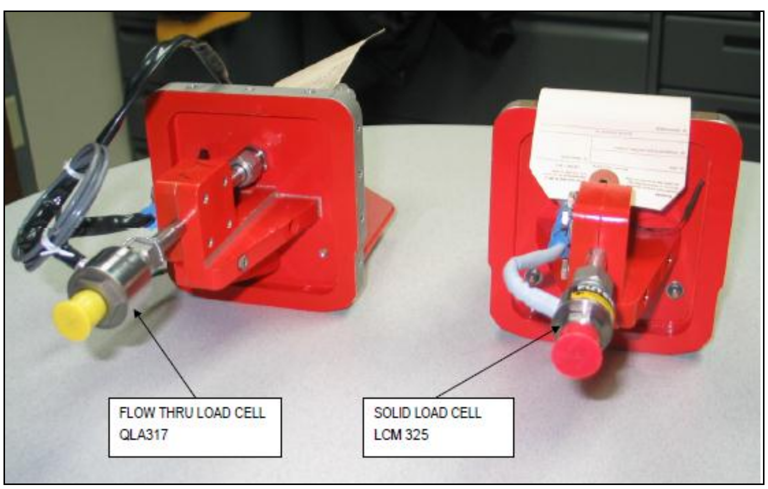

Figure 4 Pressure Tube Attachment Assemblies with Flow-Thru (Left) and Solid (Right) Load Cells Installed

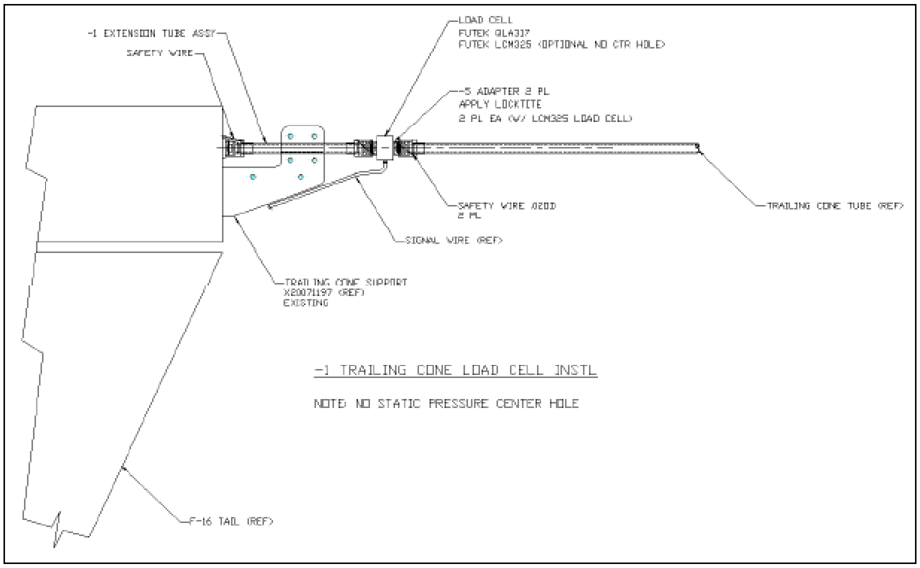

Figure 5 Trailing Cone Load Cell Installation

TEST METHODOLOGY

Tower flybys were flown at Edwards AFB in March 2007 to determine the trailing cone static source error corrections (reference 1). Digital photographs were taken of each flyby to determine the trailing cone system droop angle, which was defined as the angle between a straight line connecting the drag cone to pressure tube attachment point and the horizon reference line (Figure 6).

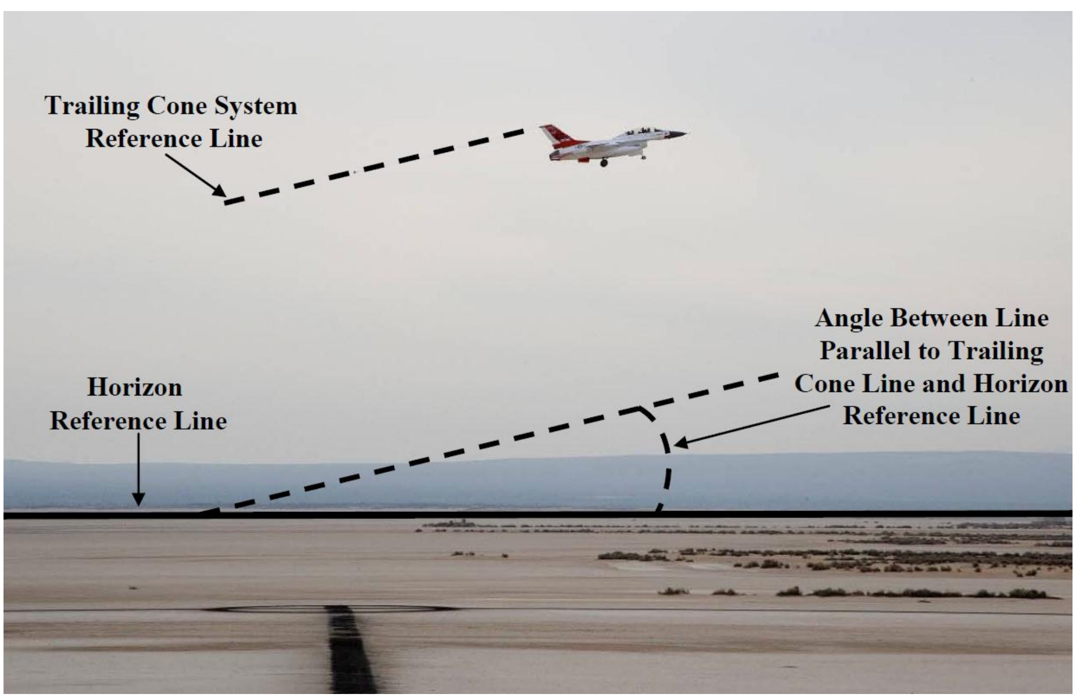

Figure 6 Method used to Determine Trailing Cone Angle of Attack (reference 1)

Trailing cone system loads were measured using the in-line load cell during tower flyby sorties in 2009 and 2010. Although the load cell continuously recorded data throughout the sorties, only loads from stabilized flight as the airplane passed the flyby tower were considered in this analysis.

ANALYSIS METHODOLOGY

The analytical method is outlined in detail in reference 2 and is summarized here. Figure 7 shows the free body diagram of the trailing cone system and shows the drag cone, pressure tube, and an elemental length of tube. The characteristics of the drag cone and pressure tube used in this analysis are listed in Table 1. The analytical method assumed a constant drag coefficient for a cone based on Hoerner's *Fluid Dynamic Drag* (reference 3). The analysis considered the difference in tube diameters between the bare pressure tube and the pressure tube sheathed with the protective fire sleeve. Differences in roughness and specific weight between the fire sleeve and the bare pressure tube were neglected.

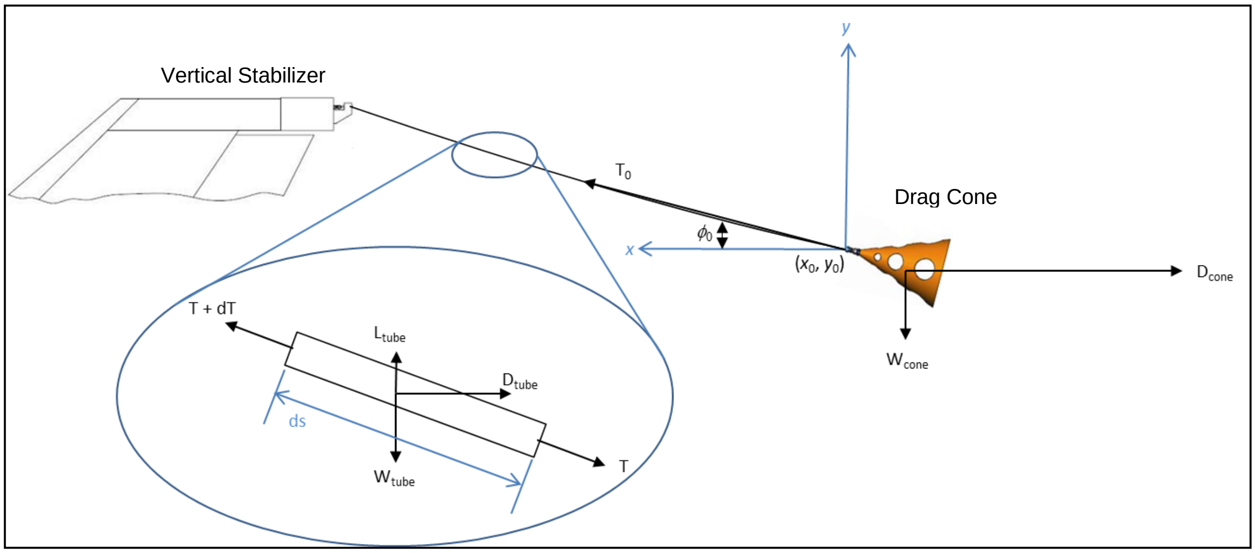

Figure 7 Free Body Diagram of Trailing Cone System

Table 1 Characteristics of Trailing Cone System Installed on the F-16 Pacer Aircraft

Tube Length, *l*	65 ft
Tube Radius (Nylaflow), r_{tube}	3/16 in
Tube Radius (Nylaflow+Kevlar Sheath)	5/16 in
Tube Specific Weight, ρ_{tube}	0.062 lb/ft
Tube Drag Coefficient, C_{D0}	1.1 (from reference 3)
Roughness Constant, *K*	0.045 (from reference 2)

Weight of Drag Cone and Swivel	1.5 lb
Diameter of Drag Cone	10 in
Base Area of Drag Cone	0.5454 ft^2
Drag Cone Half Vertex Angle, ε	21 deg
Drag Cone Drag Coefficient	0.012 ε + 0.019 = 0.4420 (from reference 3)

The trailing cone system tension, droop angle, and *x* and *y* coordinates of the pressure tube were predicted by the following system of differential equations.

$$\frac{dT}{ds} = \rho_{tube} g \sin\phi + \rho V_T^2 r_{tube} C_{D0} K \left(\frac{\pi}{2} - \phi\right)\left(2 + \phi - \frac{\pi}{2}\right) \tag{1}$$

$$T\frac{d\phi}{ds} = \rho_{tube} g \cos\phi - \rho V_T^2 r_{tube} C_{D0} \cos^2\left(\frac{\pi}{2} - \phi\right) \tag{2}$$

$$\frac{dx}{ds} = \cos(\phi) \tag{3}$$

$$\frac{dy}{ds} = \sin(\phi) \tag{4}$$

The following initial conditions were specified:

$$\begin{aligned} x_0 &= 0, y_0 = 0, \\ T_0 &= \sqrt{W_{cone}^2 + D_{cone}^2}, \\ \phi_0 &= \arctan\left(\frac{W_{cone}}{D_{cone}}\right) \end{aligned} \tag{5}$$

Equations 1 through 4 were integrated along the length of pressure tube using the Matlab® function `ODE45`. Figure 8 shows the predicted position of the pressure tube. The origin of the *x*-*y* coordinate system was located at the vertex of the drag cone. The tube was attached to the aircraft at an *x* coordinate of 65 feet. Figure 9 shows the predicted tension forces plotted versus the distance along the pressure tube, *s*. The tension force at *s* = 0 feet represented the initial tension, T_0, due to the weight and drag of the cone calculated by equation 5. The tension at *s* = 65 feet was the total of the weight and drag forces of the pressure tube and drag cone system. Figure 9 also shows that the pressure tube accounted for 26 to 30 percent of the total tension forces.

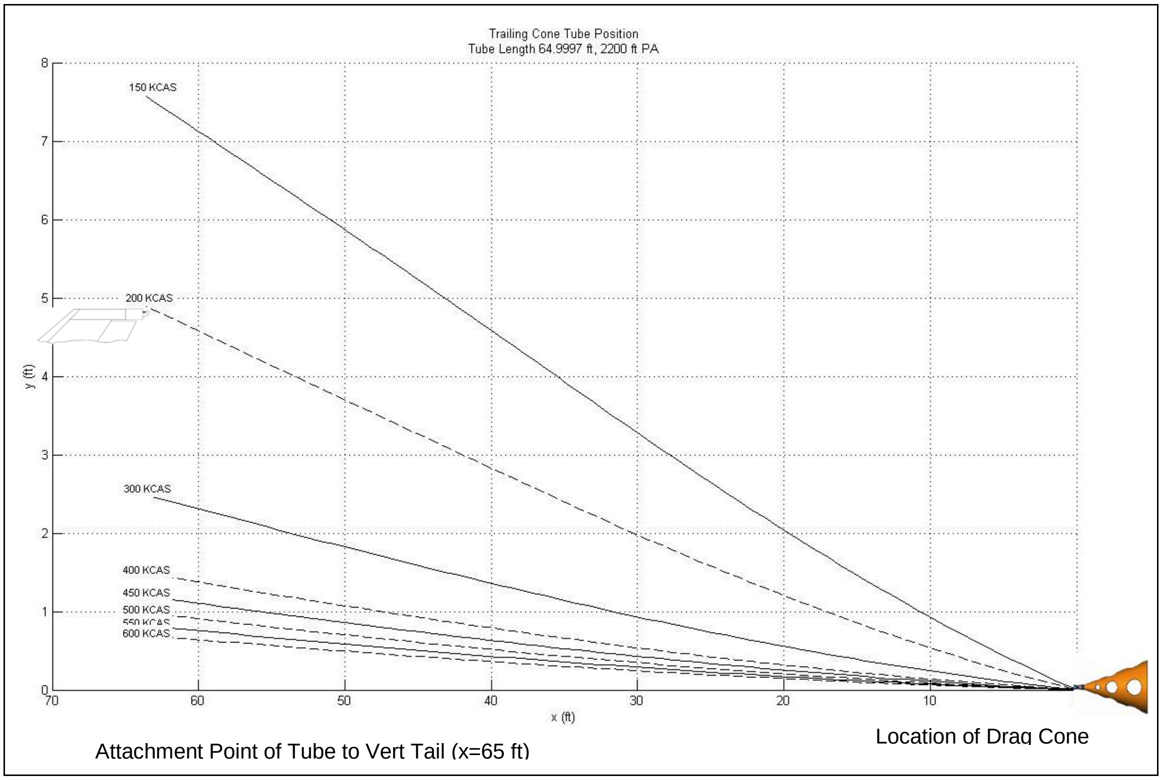

Figure 8 Predicted Position of Pressure Tube

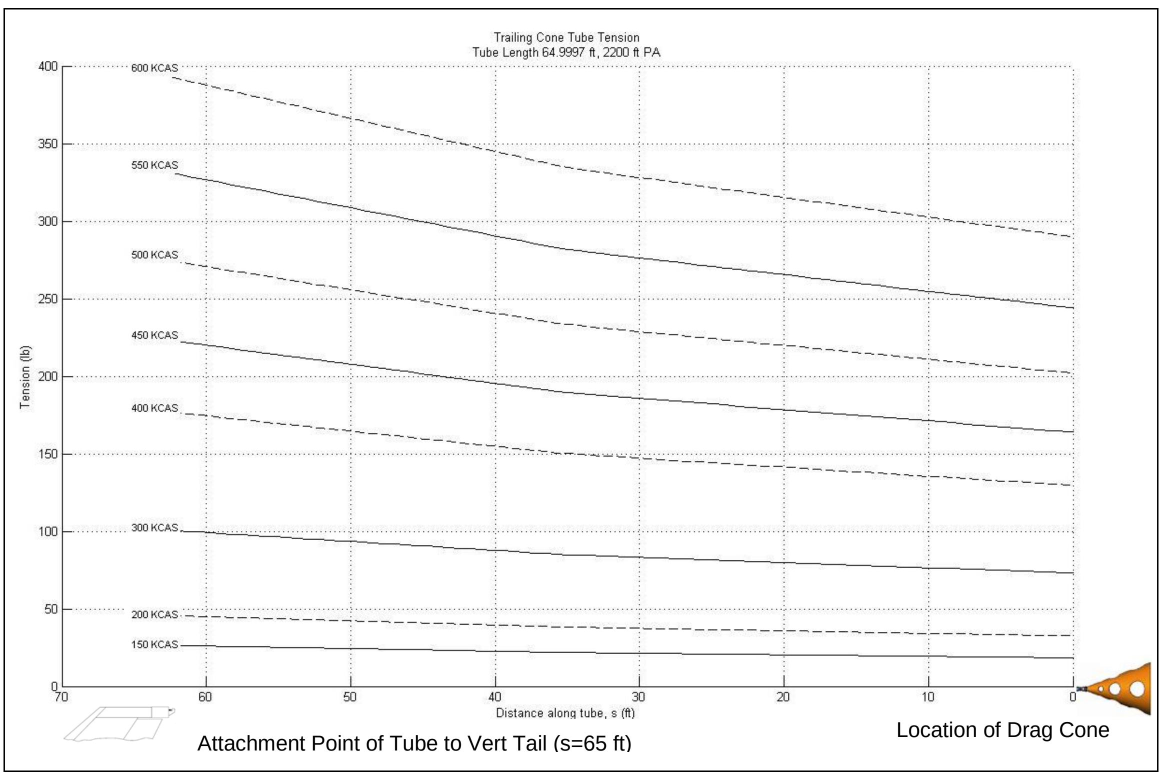

Figure 9 Predicted Tension in Pressure Tube

RESULTS

Figure 10 compares the flight test measured loads and tube angles with those predicted by the analytical method plotted versus calibrated airspeed. The top of Figure 10 shows trailing cone system tension measured between 300 and 590 KCAS at approximately 2,000 feet pressure altitude. The measured tension forces increased with airspeed and varied between 100 and 500 pounds. The tension predictions were good at airspeeds of 500 KCAS and below and matched the flight test results within approximately 10 percent. However, above 500 KCAS (0.78 Mach number), the predictions were poor and under-predicted tension by up to 100 pounds, or 20 percent.

The predicted tension was a function of the pressure tube drag and the cone drag forces, both of which were calculated based on drag coefficients from reference 3 and were assumed to be constants. The analytical method probably under-predicted the drag forces because it neglected Mach number effects on drag coefficient.

The bottom of Figure 10 shows trailing cone system angles measured between 160 and 460 KCAS. The angles decreased with increasing airspeed and varied between 14 and 0 degrees. The angle predictions were good and matched the flight test results within 1 degree at airspeeds faster than 300 KCAS. At slower airspeeds, the comparison between predicted and measured angles was poor with the analytical method under-predicting angle by as much as 8 degrees.

CONCLUSIONS

When using simple methods for estimating drag coefficients from Hoerner's *Fluid Dynamic Drag,* the analytical method presented in reference 2 predicted tension forces and tube angles that were within 10 percent and 1 degree, respectively, between 300 and 500 KCAS. At airspeeds slower than 300 KCAS, the analytical method under-predicted the tube angles by up to 8 degrees. At airspeeds faster than 500 KCAS, the analytical method under-predicted the tension force by up to 100 pounds, or 20 percent. Further work is required to improve the drag estimates and to determine the causes of the differences between predicted and measured tension forces and tube angles.

The analytical method is useful for trade studies to determine the effects of drag cone size and weight on the tube angles and tension forces.

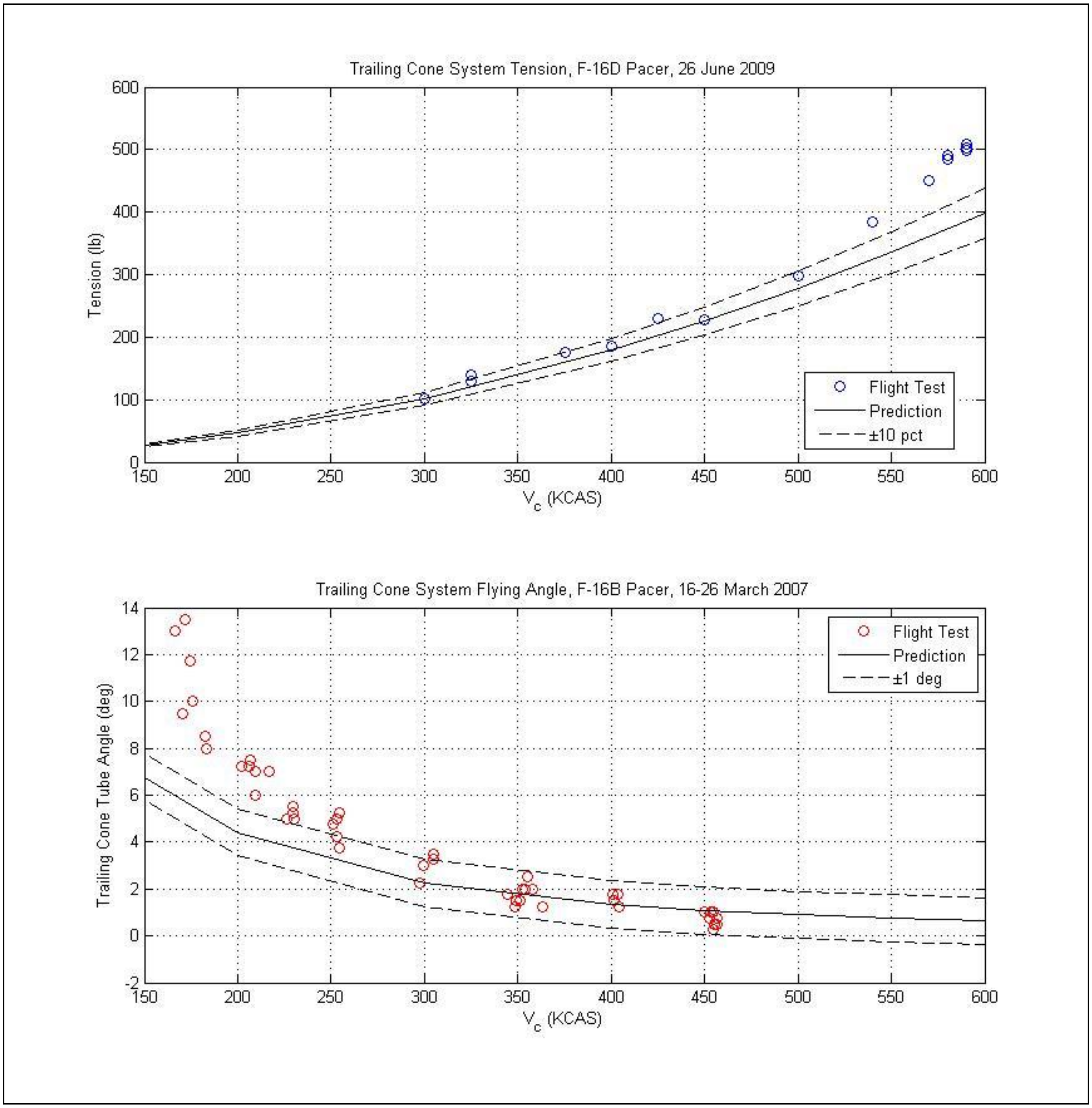

Figure 10 Summary of Trailing Cone System Drag Force and Tube Angle

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BIOGRAPHY

Reagan Woolf earned a B.S. degree in Aerospace Engineering and Mechanics from the University of Minnesota in 2000 and a M.S. in Aerospace Engineering from University of California, Los Angeles (UCLA) in 2002. Reagan works for the 412th Test Wing at Edwards Air Force Base as an aircraft performance engineer. He has worked on performance flight test programs on the T-38A/C, C-130H, RQ-4 Global Hawk, and T-53A and air data calibration programs on the T-38C, F-117, F-15, F-16, C-130, F-22A, B-52, B-2, and X-47B. He is currently the 412th Test Wing aircraft performance technical expert. Reagan is a member of SFTE and AIAA.